PHYSICAL PARAMETERS OF THE CEN X-3 SYSTEM

Patrick S. Osmer

Cerro Tololo Inter-American Observatory*

W. A. Hiltner†

University of Michigan

J. A. J. Whelan

Institute of Astronomy, Cambridge

Abstract. Photographic spectra of Cen X-3 show that the primary star has a spectral type near O6.5 with weak, variable emission at λλ4640 and 4686. No orbital motion of the emission or absorption lines is detected; for the latter the upper limit is ~±50 km s^{-1}. Analysis of the available data indicates that the primary is a factor of 2-3 less massive than expected from normal evolutionary models while the X-ray source has a mass near 1.5 $M_\odot$.

(NASA-CR-139569) PHYSICAL PARAMETERS OF THE CEN X-3 SYSTEM (Cerro Tololo Inter-American Observatory) 10 p HC $4.00 CSCL 03A

N74-31322

Unclas

G3/30 46651

*Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

†Visiting Astronomer, Cerro Tololo Inter-American Observatory.

The Cen X-3 system is the only binary X-ray source with a massive companion for which both the orbital parameters of the X-ray source (Schreier et al. 1972) and the optical ellipsoidal light curve (Krzeminski 1973, 1974, Petro (1974) have been determined. Consequently it is the only massive system for which a fundamental determination of parameters such as the radius of the primary and masses of the components can be made. In this paper we present spectroscopic observations of the primary star which yield a spectral type near O6.5 and an intermediate luminosity class. Then consideration of Krzeminski's light curve shows that the primary is a third to half as massive as expected from normal evolutionary models while the X-ray source is more massive than originally thought. In the accompanying paper, Petro (1974) reaches similar conclusions from a detailed, independent analysis of a new light curve obtained by him.

We used the Cassegrain spectrograph on the Cerro Tololo 1.5-m telescope to obtain 102 Å/mm, 0.3 mm wide spectrograms on nitrogen-baked IIa-O emulsion. We made six exposures of Cen X-3: two of 4 hr on 1974 Mar 18 and the rest of 7 hr on 1974 Mar 19, 23, 24, and 29 (Table 1). The coverage in phase was satisfactory except for a gap between 0.1 and 0.4 (phase 0.0 corresponds to X-ray eclipse). Since the 7 hr exposures covered 1/7 of the orbital period, there was a loss of time resolution. However, for a first reconnaissance of the system, especially in view of the rather weak-lined nature of O star spectra, we judged that the long exposures were preferable to using an image tube.

Examination of the spectra (Figure 1) leaves no doubt that lines of H,

He I, and He II are present in absorption. Both λλ4200 and 4541 of He II are seen, and their approximate equality, on the average, with λλ4026 and 4471 of He I, respectively, suggests a spectral type near O6.5. The rapid decrease of the He II/He I ratio with advancing spectral type means that the star cannot be much later than O7. Although the visibility of the absorption lines is not the same on all plates, it is difficult to estimate how significant the differences are relative to the plate noise. On plate C-3988 (Figure 1b) He II λ4541 is not seen and Hγ is weak. Hδ appears to have a P Cyg profile. However, the He II λ4200/He I - He II λ4026 ratio is approximately the same as on plate C-3979 (Figure 1a), for example, which rules out a large change in temperature. Spectrograms with a higher signal-to-noise ratio are needed to make a more accurate classification and settle the question of variability.

Weak, ill-defined emission can be seen on the spectrograms at λλ4640 and 4686. There is no obvious variation of the emission-line velocities with time, which are not distinguishably different from the absorption-line velocities. At our dispersion Cen X-3 is very similar to HD 153919 = 2U1700-37 (Figure 1e) except for having weaker emission, which implies that the primary star has a lower luminosity, probably near class II or III.

The main difference between our results and those of Rickard (1974) and Vidal <u>et al</u>. (1974), who derived a spectral type of O9-B0 from image tube spectrograms, is that our plates show the presence of He II λλ4200 and 4541 in absorption. Note that the absence of He II λ4686 in absorption is not in itself an argument against the earlier spectral type found by us since the line changes from absoprtion to emission with increasing luminosity. Our experience indicates that photographic spectra are to be preferred for classifying O stars

because weak absorption lines are more difficult to see on image tube spectra of similar dispersion. There is, of course, the possibility of a long-term variation in spectral type of Cen X-3, but the lack of such variation in other massive X-ray binaries and the low ratio of X-ray luminosity to total optical luminosity in Cen X-3 do not provide support for the idea at present.

Radial velocity measures of the absorption lines show a wide scatter on any one plate and the mean of the λ3835, Hγ, and λ4471 velocities (the lines most readily measurable) shows no obvious variation with phase (Table 1). Fitting a sine curve to the results gives residuals indistinguishable from fitting a straight line, 38 km s^{-1} in the mean. The interstellar K-line velocity is -12 km s^{-1} with an rms deviation of 22 km s^{-1} for a single plate.

The velocity data for the absorption lines give an upper limit for the semi-amplitude of the orbital motion of the primary of about 50 km s^{-1}. Since the corresponding velocity of the X-ray source is 400 km s^{-1} (Schreier et al. 1972) an upper limit for the mass ratio $q = M_x/M_{primary}$ is 1/8. That this limit is already of some significance, and very important to improve upon, is apparent from consideration of the ellipsoidal light curve.

We have taken advantage of the visit of one of us (P.S.O.) to Cambridge to bring the results of a different light-curve synthesis program (that of J.A.J.W) together with those given by Petro (1974). Several groups have developed such programs, but there has been little direct comparison of the results published as yet. In the following discussion we consider the implication of the X-ray orbital data, the amplitudes of Krzeminski's light curve (Petro's

data were not available then), and the spectroscopic results just described. Petro (1974) presents in the accompanying paper a comprehensive analysis of his new light curve.

The observations of Krzeminski (1974) indicate that the depths of the minima in V are $\Delta m_1 = 0.09 \pm 0.02$ mag at phase 0.5 and $\Delta m_2 = 0.07 \pm 0.02$ mag at phase 0.0. These values are larger than predicted by Wilson (1972) from calculations of the light curve that satisfy the duration of the X-ray eclipse (Schreier et al. 1972). Wilson derived an upper limit of $q \sim 0.02$ on the assumption the X-ray eclipses are produced by the stellar photosphere at its Roche limit. However, a larger mass ratio is necessary to produce the observed light curve; to be consistent with the observed eclipse duration this implies either that the primary overfills its Roche lobe, perhaps as described by Weedman and Hall (1972), or that X-ray occulting material extends beyond the photosphere.

Using a light-curve synthesis program based on that described by Strittmatter et al. (1973), which assumes co-rotation, we constructed a series of light curves for conditions appropriate to Cen X-3: temperatures of 30,000° and 40,000°K at the "back" of the primary, no X-ray heating, inclination of the orbit, i, = 90°, and mass ratios $0.018 \leq q \leq 0.20$. The effects of altering the input parameters to include (1) overfilling or under-filling the Roche lobe, (2) a small amount of X-ray heating, and (3) a decrease of inclination i are illustrated in Figure 2 of Whelan (1973), where further details of the technique may also be found (see also Hutchings 1974). The first two effects are small here. Solutions of the light-curve amplitudes alone are possible as i decreases, but the resulting increase in q is limited both by the long eclipse, which can hardly be satisfied even at 90°, and the upper bound on the orbital velocity of the primary. All presently available

data require that $i \sim 90°$.

We adopt $i \sim 90°$ and $q \sim 0.08$ as the solution which gives the best fit to the amplitudes of the light curve and note that it implies an orbital velocity of ~33 km s^{-1} for the primary, well within the observed limit, and an eclipse angle ϕ_E of 37°. Although 37° is below the formal lower bound of 42° of Schreier et al. (1972), it is not unreasonable in view of the possibility of the primary overfilling the Roche lobe or that a region which is larger than the photosphere, opaque to X-rays, and caused by a stellar wind may exist (Pringle 1973).

When combined with the X-ray mass function and a primary T_e of ~36,000°, the solution implies that

$$M_{primary} = 18 \pm 1\ M_{\odot} \qquad M_{X\text{-}ray} = 1.4 \pm 0.4\ M_{\odot}$$

$$R_{primary} \sim 12\ R_{\odot} \qquad \text{and} \qquad L_{primary} \sim 1 \times 10^{39}\ \text{erg s}^{-1}$$

where R is the equivalent spherical radius. The derived luminosity is consistent with that of an O6.5 III star and indicates a distance of ~10 kpc. The corresponding X-ray luminosity is ~3×10^{37} erg s^{-1}. The mass of the X-ray object is plausible and shows that it need not be of very low mass (Sofia 1972, Wilson 1972). We especially note: (1) the primary cannot be a low-mass highly evolved star, regardless of the value of i; (2) $M_{primary} \ll 50\ M_{\odot}$, which is the mass value derived from the luminosity and normal stellar models (Papaloizou and Whelan 1973); (3) $L_{primary}$ (Cen X-3) ~ $L_{primary}$ (SMC X-1), for which the luminosity is known independently; and (4) the primary mass of Cen X-3 is similar to that estimated by Osmer and Hiltner (1974) for SMC X-1.

Evidently, the masses of the optical counterparts of the X-ray binaries should not be derived solely by fitting spectral types and luminosities to evolutionary models; rather the masses must be determined directly from the radial velocity and light curve data. For this reason it appears to be premature to conclude that 2U0900-40 (Wickramasinghe et al. 1974) and 2U1700-37 (Bessell et al. 1974) are black holes.

We are indebted to Mark Hanna for the photographic work involved in producing Figure 1 and to Klaus Czuia for assistance at the telescope. We also thank Dr. Nolan Walborn for useful discussions. This work was supported in part by NASA under grant NGR 23-005-464.

TABLE 1

Spectroscopic Observations

Plate	J.D. 2442	Phase	Heliocentric radial velocity ($km\ s^{-1}$)*
C-3977	124.601	0.54	-47
C-3978	124.783	0.63	- 7
C-3979	125.697	0.07	57
C-3988	129.704	0.99	20
C-3991	130.683	0.46	-44
C-3993	135.660	0.84	-15

*Mean of λ3835, Hγ, and λ4471 velocities. Mean error of a single value ~30 $km\ s^{-1}$.

REFERENCES

Bessell, M. S., Peterson, B. A., Wickramasinghe, D. T., and Vidal, N. V. 1974, Ap. J., 187, 355.

Hutchings, J. B. 1974, Ap. J., 188, 341.

Krzeminski, W. 1973, I.A.U. Circular No. 2612.

__________. 1974, Ap. J. Letters, in press.

Osmer, P. S., and Hiltner, W. A. 1974, Ap. J. Letters, 188, L5.

Papaloizou, J. C. B. and Whelan, J. A. J. 1973, M.N.R.A.S., 164, 1.

Petro, L. D. 1974, Ap. J. Letters, preprint.

Pringle, J. E. 1973, Nature Phys. Sci., 243, 90.

Rickard, J. J. 1974, Ap. J. Letters, 189, L113.

Schreier, E., Levinson, R., Gursky, H., Kellogg, E., Tananbaum, H., and Giacconi, R. 1972, Ap. J. Letters, 172, L79.

Sofia, S. 1972, Ap. J. Letters, 174, L31.

Strittmatter, P. A., Scott, J., Whelan, J., Wickramasinghe, D. T., and Woolf, N. J. 1973, Astr. and Ap., 25, 275.

Vidal, N. V., Wickramasinghe, D. T., Peterson, B. A., and Bessell, M. S. 1974, Ap. J. Letters, in press.

Weedman, D. W., and Hall, D. S. 1972, Ap. J. Letters, 176, L19.

Whelan, J. 1973, Ap. J. Letters, 185, L127.

Wickramasinghe, D. T., Vidal, N. V., Bessell, M. S., Peterson, B. A., and Perry, M. E. 1974, Ap. J., 188, 167.

Wilson, R. E. 1972, Ap. J. Letters, 174, L27.

FIGURE CAPTION

Figure 1. Spectra of the Cen X-3 primary and associated comparison stars. (a) Cen X-3, plate C-3979, phase 0.07; (b) Cen X-3, plate C-3988, phase 0.99; (c) Cen X-3, plate C-3991, phase 0.46; (d) Cen X-3, plate C-3993, phase 0.84; (e) HD 153919 = 2U1700-37; (f) 15 Mon, MK standard; (g) λ Ori, MK standard; (h) ι Ori, MK standard. The strength of the He II absorption lines in Cen X-3 indicate that its spectral type is similar to that of HD 153919 but the weaker emission at λλ4640 and 4686 implies a lower luminosity.